Example 4g: Laminate Yield Surface Analysis

This example problem illustrates the laminate yield surface capabilities within MAC/GMC 4.0. In particular, a cross-ply 0.25 fiber volume fraction SiC/Ti-21S laminate, with each layer represented by the 7×7 circular fiber cross-section approximation RUC architecture, is examined. For the RUC yield surface analyses presented in Example 4f, the stress space was defined by global stress quantities. For laminate yield surface analysis, the global loading quantities are force resultants, which define the force resultant space for the yield surface. In accordance with the plane stress formulation of lamination theory, only in-plane yield surfaces may be generated for laminates. Yield surfaces that involve bending of the laminate may not be generated. Additional options are available for laminate yield surface analysis as yield surfaces can be generated on the level of the laminate, the ply, and the individual subcells that constitute each ply.

MAC/GMC Input File: `example_4g.mac`

```
MAC/GMC 4.0 Example 4f - Laminate yield surface analysis
*CONSTITUENTS
  NMATS=2
  M=1 CMOD=6 MATID=E
  M=2 CMOD=4 MATID=A
*LAMINATE
  NLY=3
  LY=1 MOD=2 THK=0.25 ANG=0  ARCHID=6 VF=0.25 R=1. F=1 M=2
  LY=2 MOD=2 THK=0.50 ANG=90 ARCHID=6 VF=0.25 R=1. F=1 M=2
  LY=3 MOD=2 THK=0.25 ANG=0  ARCHID=6 VF=0.25 R=1. F=1 M=2
*SURF
  TMAX=400. STP=0.05 MMAX=0.04 MODE=1 TREF=650.
  OPTION=1,2,3,4,5,6,7
  ISPX=1 ISPY=2 ANGINC=5.
  EPS=0.0001 DR=0.00025 ISR=0.00002 IP=0.001
*PRINT
  NPL=0
*END
```

Annotated Input Data

1) Flags: None

2) Constituent materials (**`*CONSTITUENTS`**) [KM_2]:

Number of materials:	2	(`NMATS=2`)
Materials:	SiC fiber	(`MATID=E`)
	Ti-21S	(`MATID=A`)
Constitutive models:	SiC fiber: linearly elastic	(`CMOD=6`)
	Ti-21S matrix: Isotropic GVIPS	(`CMOD=4`)

3) Analysis type (**`*LAMINATE`**) → Laminate Analysis [KM_3]:

Number of layers:	3	(`NLY=3`)

Layer	Analysis Model	Thickness	Fiber Angle	Architecture	Aspect Ratio	Volume fraction	Fiber material	Matrix material
(LY=)	(MOD)	(THK)	(ANG)	(ARCHID)	(R)	(VF)	(F)	(M)
1	GMC-2D	0.25	90°	7×7 circle, rect. pack	1.	0.25	SiC	Ti-21S
2	GMC-2D	0.50	0°	7×7 circle, rect. pack	1.	0.25	SiC	Ti-21S
3	GMC-2D	0.25	90°	7×7 circle, rect. pack	1.	0.25	SiC	Ti-21S

4) Loading:

a) Mechanical (**`*MECH`**) [KM_4]: no mechanical preloading

b) Thermal (**`*THERM`**) [KM_4]: no thermal preloading

c) Time integration (**`*SOLVER`**) [KM_4]: no preloading

d) Yield surface generation (**`*SURF`**) [KM_4]:

Maximum probing time:	400. sec.	(TMAX=400.)
Probing time step size:	0.05 sec.	(STP=0.05)
Maximum probing load:	0.04	(MMAX=0.04)
Probing mode:	strain control	(MODE=1)
Reference temperature:	650. °C	(TREF=650.)
Yield surface options:	Generate global (laminate) data (1) Generate 1st ply data (2) Generate all plies data (3) Generate data for each ply (4) Generate 1st subcell data (5) Generate all subcells data (6) Generate local subcell data (7)	(OPTION=1,2,3,4,5,6,7)
Force resultant space x-axis:	N_{xx}	(ISPX=1)
Force resultant space y-axis:	N_{yy}	(ISPY=2)
Probe angle increment:	5.°	(ANGINC=5)
Quantities defining yield:	Equivalent plastic strain = 0.0001	(EPS=0.0001)
	Dissipation rate = 0.00025	(DR=0.00025)
	Inelastic strain rate = 0.00002	(ISR=0.00002)
	Inelastic power = 0.001	(IP=0.001)

For laminate analysis, the yield surface option (**`*SURF`**) generates up to seven ASCII files that contain the yield surface data. `surf_global.dat` contains the global (i.e., laminate level) yield surface data for each type of yield surface (i.e., EPS, DR, ISR, and IP), `surf_1st_ply.dat` contains the yield surface data based on first ply yield for each type of yield surface, `surf_all_plies.dat` contains the yield surface data based on the requirement that all plies (that can yield) yield for each type of yield surface, `surf_plies.dat` contains the yield surface data for each individual ply for each type of yield surface, `surf_1st.dat` contains the yield surface data based on first subcell yield for each type of yield surface, `surf_all.dat` contains the yield surface data based on the requirement that all subcells (that can yield) yield for each type of yield surface, and `surf_local.dat` contains the yield surface data for each individual subcell for each type of yield surface. Thus, laminate analysis adds an additional level in the yield surface data hierarchy.

☞ Note: In general, the quantities necessary for determining global (laminate level) yield are not present in standard lamination theory. That is, for instance, lamination theory calculates laminate level inelastic force resultants rather than laminate level inelastic strains, which are needed for evaluation of yielding. Therefore, for use within the yield calculations, MAC/GMC 4.0 determines effective laminate level quantities when appropriate.

5) Damage and Failure: None

6) Output:
a) Output file print level (**`*PRINT`**) [KM_6]:
Print level: 0 (`NPL=0`)

b) x-y plots (**`*XYPLOT`**): None

7) End of file keyword: (**`*END`**)

Results

Figure 4.17 presents the four global (laminate level) yield surfaces generated in this example. Because a $[0°/90°]_s$ laminate is simulated and residual stresses are not included, a particular yield surface crosses each axis at the same force resultant magnitude. In addition, the yield surfaces are less elongated than those that correspond to the continuous SiC/Ti-21S composite in Figure 4.10.

Figure 4.18 shows additional equivalent plastic strain (EPS) yield surfaces. The yield surfaces generated based on yield of the 0° ply and the 90° ply intersect (much like the subcell-based yield surfaces intersect in Figure 4.12). The yield surface based on first ply yield traces the intersection of the individual ply curves, while the yield surface based on requiring yield of all plies traces the union. Also plotted in Figure 4.18 is the EPS yield surface based on first subcell yield. This is the smallest surface plotted because it is based on yielding of any subcell in any of the plies. Conversely, the yield surface based on requiring yielding of all subcells in all plies tends to be large. At certain locations, however, the global laminate yield surface is larger than the all subcells yield surface because the global yield surface is based on volume-average quantities, which include the 0.25 volume fraction fiber. Thus, while the subcell-based yield surfaces relate to the matrix material occupying the particular subcell, the laminate (and ply) level yield surfaces have averaged in the effect of the elastic fiber (which contributes zero plastic strain).

Figure 4.19 shows the yield surfaces associated with each of the individual subcells within each layer. The first subcell yield surface and the all subcells yield surface automatically select the intersection and union, respectively, of the individual subcell yield surfaces.

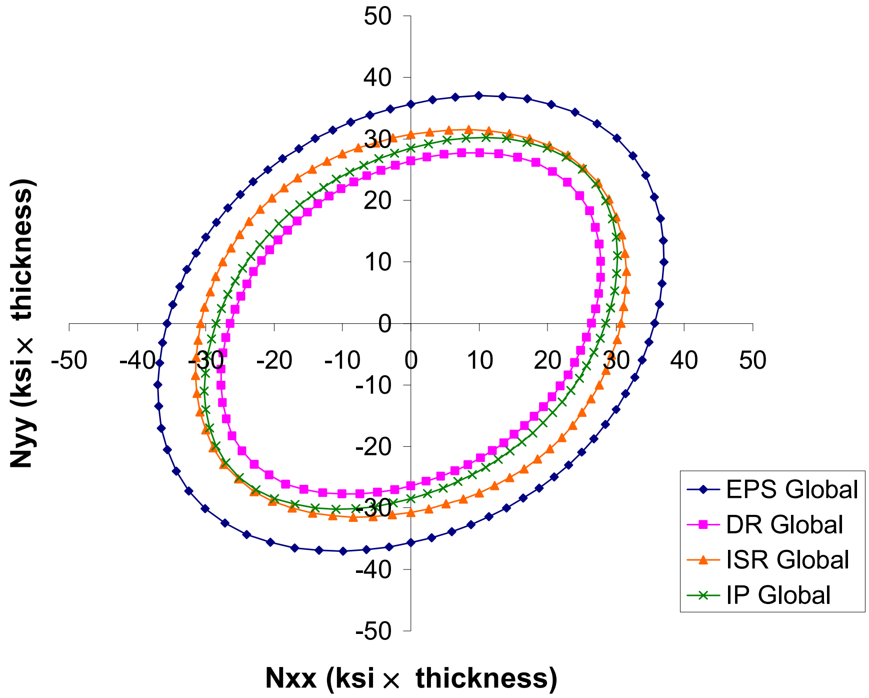

Figure 4.17 Global (laminate) yield surfaces for a 0.25 fiber volume fraction [0°/90°]$_s$ SiC/Ti-21S laminate.

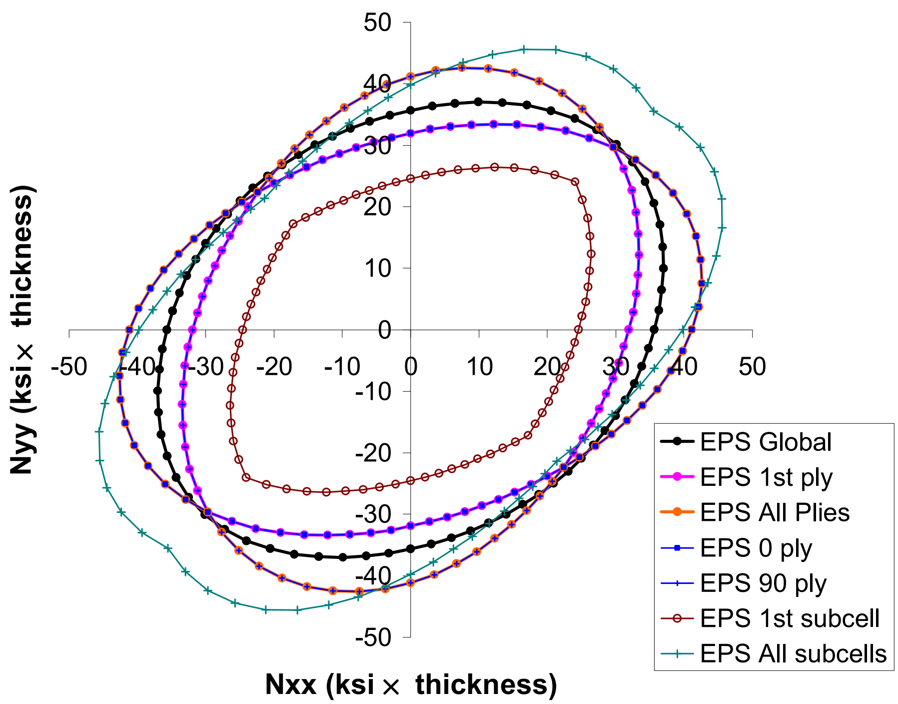

Figure 4.18 Equivalent plastic strain (EPS) yield surfaces for a 0.25 fiber volume fraction [0°/90°]$_s$ SiC/Ti-21S laminate.

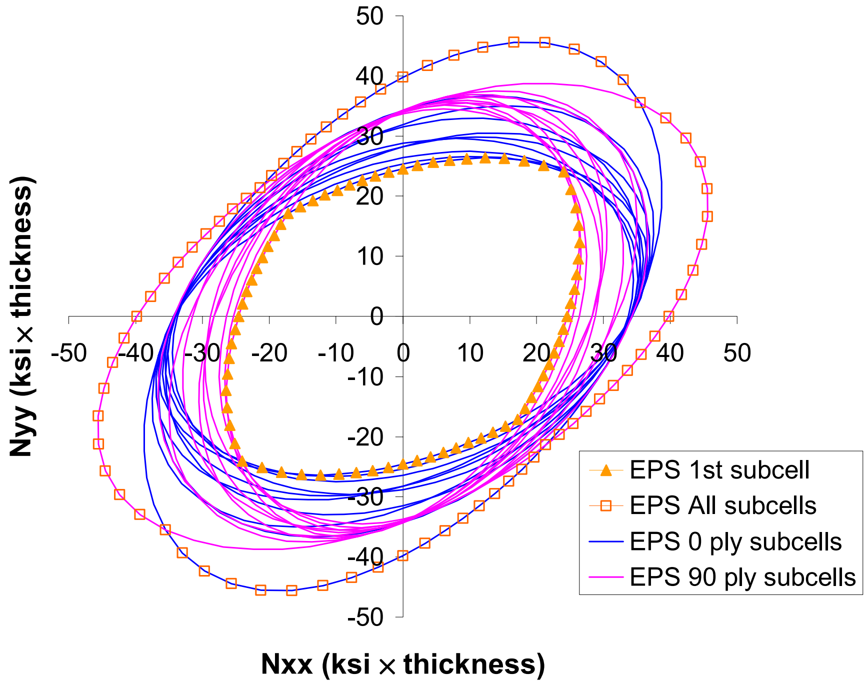

Figure 4.19 Subcell-based equivalent plastic strain (EPS) yield surfaces for a 0.25 fiber volume fraction $[0°/90°]_s$ SiC/Ti-21S laminate.